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Experimental Demonstration of $V_p \times B$ Acceleration Scheme with Use of Transverse Electromagnetic Waves

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Abstract

Electron linear acceleration, using a slow transverse electromagnetic wave (TE wave) supplemented with a crossed static magnetic field, has been demonstrated. An energy gain of 3.5 keV is measured for electrons with a 64 keV incident energy, in a 0.5 m long accelerator, when an external magnetic field of 0.67 G is applied. The results show the feasibility of a high gradient, compact accelerator using TE mode intense laser or short wave length microwave without slow wave structure or mode converter.

I. Introduction

An accelerator is proposed in which a TE-mode wave is used to drive charged particles in contrast with the usual linear accelerators based on the $v_p \times B$ acceleration mechanism in which longitudinal electric fields or TM-mode waves are supposed to be used.[1~6] Using TE mode as a driving wave allows higher gradient and more compact accelerators, because the slow wave structure, or mode converter, is not necessary for high energy accelerators. In this paper, we report results of proof of principle experiments on the $v_p \times B$ acceleration scheme using the TE wave in vacuum. In order to couple particles with the transverse wave we use a slow wave structure created waveguide composed of parallel dielectric materials and of conductors.[2]

II. Theory

Suppose that the transverse electromagnetic wave which has a maximum electric field E_x and a maximum magnetic field B_y in the x and y direction, respectively, propagates with a phase velocity v_p in the z direction (see Fig. 1) . When an external static magnetic field B_0, with an amplitude smaller than B_y is applied in the y direction, there exist two magnetic neutral points (A and B) where the electric field is non-zero. Around point B, the Lorentz force acts on the particles with its velocity, $v \approx v_p$, which are accelerated by the electric field in the x direction, in the z direction as restoring force. Therefore the particles bunch there and are accelerated by the wave electric field in the x direction, continuously.

The motion of a charged particle with the rest mass, m, and charge, q, in the above-mentioned system is described by the equation of motion.[2] The trapping condition is obtained by the balance of the equation of motion in the wave propagation direction (z direction) such as,

$$|B_y| > \gamma_p^2 B_0. \tag{1}$$

where γ_p is the Lorentz factor measured with the wave phase velocity, v_p. Inequality represents the unlimited acceleration condition. In other words, if this condition is satisfied, electrons can be accelerated continuously without detrapping from the wave trough.

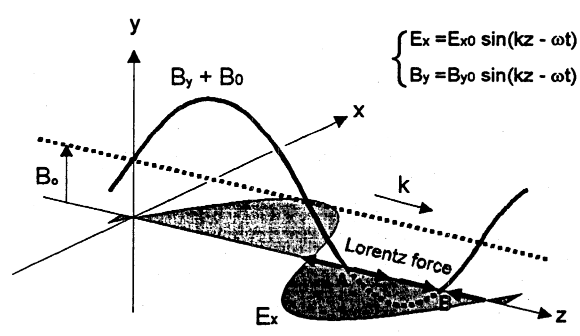

Fig.1. Schematic diagram of the $v_p \times B_0$ acceleration using a transverse electromagnetic wave. An electromagnetic wave with a transverse electric field component propagates in the z direction with the phase velocity v_p. A static magnetic field B_0 is applied in the y direction. A charged particle is accelerated in the x direction.

III. Experimental set-up and results

A schematic view of the experimental set-up is shown in Fig. 2(a). The injected electrons with beam

Table I. Dimensions of the dielectric wave guide.

Dielectric materials	Macorl and Folsteright
Accelerator length	48 cm
thickness Δd	50 mm
width $2h$	50 mm
separation $2d$	13~33 mm
hight $\ell(=2d+2\Delta d)$	113~133 mm

current: 1 mA are initially accelerated, by a high-voltage DC power supply, up to a maximum energy of 100 keV. Here, we use a Pierce-type gun with a hair-pin-type cathode which is made of a tungsten filament originally made for an electron microscope. The acceleration section has a slow-wave structure of TE mode[2] and a schematic view of this structure is shown in Fig. 2(b). This structure is designed so that the phase velocity is $0.46c$ (corresponding energy of 65 keV) by adjusting the seperation to a value 74 mm. The dimensions of the slow wave structure are listed in Table I. This structure consists of 20 dielectric blocks and 48 cm long in the wave propagation direction. The blocks are installed upper and lower side of the wave guide with the separation for the electron path.

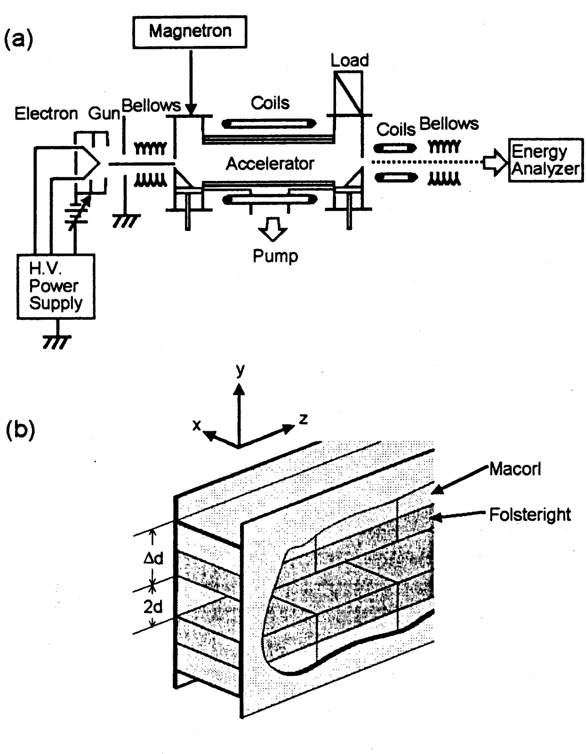

Fig.2. Experimental apparatus and the crossectional view of the wave guide loaded dielectric material. (a) Experimental apparatus for the proof of the principle of the electron accelerator using TE wave. (b) Schematic drawing of the dielectric wave guide.

The electrons accelerated through the accelerator are analyzed by a magnetic field bending type energy analyzer which has a uniform magnetic field of 200 G. The electrons are detected by a microchannel plate (MCP) electron multiplier with a slit of 2 mm in front of it. The MCP is scanned spatially in the analyzer and the position at which the signal is detected from the MCP corresponds to the energy and the signal intensities to the electron fluxes. The maximum resolution of the energy analyzer is less than 0.1 keV. This instrument is calibrated with the above-mentioned electron beam source. The calibration is carried out by changing the acceleration voltages without RF power before and after the main experiments. In the experiments, the orbit of the electrons is bent by the applied magnetic field. When the electron energy was measured, the energy analyzer is adjusted such that the electrons are injected nomal to its slit inlet.

A pulsed electromagnetic wave, with a 10 kW maximum power, is generated by a magnetron which is triggered by an external timer with a typical pulse width of 5 μs with repetition of 10 Hz. The generated microwave is absorbed by a nonreflection dummy load after going through the slow-wave structure.

The static, vertical magnetic field for the $v_p \times B_0$ acceleration is generated by a pair of saddle-shaped external coils. Uniformity less than 3 % covers length of 32 cm (40 cm for 5 %) in the z direction and 5 cm in the y direction. A maximum field strength of 10 G is measured at the center of the accelerator. This value is high enough to demonstrate the $v_p \times B_0$ principle with TE mode under the present experimental parameters.

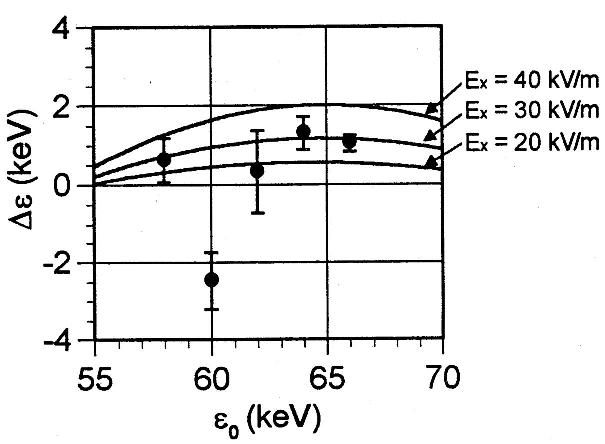

Fig.3. Energy increment, $\Delta\varepsilon$, as a function of the incident elcetron energy, ε_0, without external magnetic field. Incident microwave power : $P = 10$ kW. The solid lines indicate the calculated maximum energy increment, at the maximum electric field value of E_x = 20, 30 and 40 kV/m.

Figure 3 shows the electron energy increment as a function of incident electron energy ε_0 with no externally applied magnetic field. The maximum electron energy increment, $\Delta\varepsilon = 1.3$ keV, is observed when the incident electron energy ε_0 is 64 keV. This implies that this slow wave structure is resonated with the frequency of 2.45 GHz, and the phase velocity is corresponded to the energy of the order of 64 keV. The vertical error bars indicate the variation in electron energy due to the instability of beam transparency arised from the induced space charge on the dielectric surface through the wave guide. The resonance at the electron energy of 64 keV is slightly smaller than the designed value of 65 keV. The results show that an efficient acceleration is occured when the wave phase velocity is slightly larger than the beam velocity. A strong deceleration is observed for electrons with an energy $\varepsilon_0 = 60$ keV. In Fig. 3 the calculated results of the electron energy increment are also displayed by solid lines when the wave electric field is $E_x = 20$, 30 and 40 kV/m (shown in the next section).

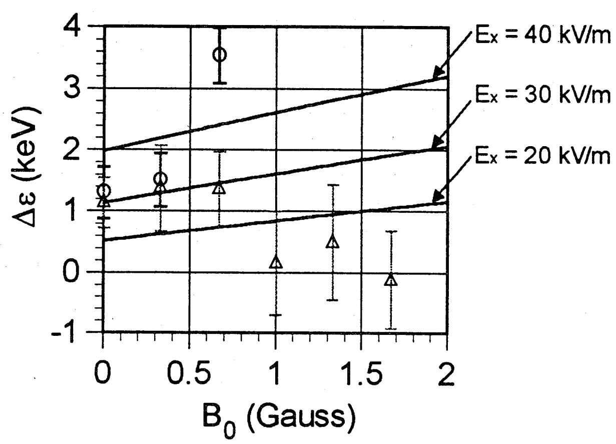

Fig.4. Energy increment, $\Delta\varepsilon$, as a fuction of the static magnetic field B_0 with $P = 10$ kW. The solid lines show the calculated values when $E_0 = 20$, 30 and 40 kV/m. Symbols ○ and △ stand for $\varepsilon_0 = 64$ keV and 66 keV, respectively.

Figure 4 shows the electron energy increment as a function of an external applied magnetic field. Symbols ○ and △ stand for values of the incident electron energy of $\varepsilon_0 = 64$ and 66 keV, respectively, and solid lines are the calculated results with an electric field amplitude $E_x = 20$, 30 and 40 kV/m. In Fig. 4, as the static magnetic field is increased, the electron energy increases until $B_0 = 0.67$ G at $\varepsilon_0 = 64$ keV. A maximum energy increment of 3.5 keV is observed at the incident energy of 64 keV with an external magnetic field of 0.67 G.

IV. Discussion

The energy increment is computed by solving the equation of motion of an electron for the parameters of the present experiment, assuming $v_p = 0.461c$, $E_x = 20$, 30 and 40 kV/m and $\tau = 3.2$ ns, where τ is the time that the electrons travel throughout the wave guide. The electric field strengths are estimated from the distribution of an incident microwave power in the wave guide. The Runge-Kutta method is used to these calculations with 100 test particles uniformly distributed initially in the phase space. Although the profile of the electric field amplitude in the wave guide depends on the position, we select the value on the axis of the waveguide, because almost all electrons propagate through the center of the wave guide in the present experiments. In the present experiment, the trapping condition inequality (Eq. (1)) is violated, because it takes more than 20 ns to reach the steady state. When $E_x = 30$ kV/m , it is good agreement with the experimental deta in Fig. 3. Therefore the assumption on the intensity of the electric field is reasonable to energy increment the electron motion in the wave guide. In Fig. 4 , the observed energy increment is larger than the calculated value. This discrepancy is not clarified yet. The condition of the transient state, however, should be taken into consideration for more precise explanation of the experimental results.

V. Conclusion

Electron acceleration using a slow transverse electromagnetic wave (TE wave) supplemented with a static magnetic filed has been demonstrated. An energy gain of 3.5 keV for electrons is observed from an incident energy of 64 keV in a 0.5 m accelerator, when an external magnetic field of 0.67 G is applied. The results show the feasibility of high gradient compact accelerator using an intense laser or short wave length microwave without slow wave structure.

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